ELEMENTS OF INTERSECTION DESIGN AND LAYOUT

Introduction

In this lecture, the selection of appropriate control measures for intersections was addressed. Whether signalized or unsignalized, the control measures implemented at an intersection must be synergistic with the design and layout of the intersection.

The elements treated here include techniques for determining the appropriate number and the use of lanes at an intersection approach, channelization, right- and let-turn treatments, special safety issues at intersections, and location of intersection signs and signal displays. There are a number of standard references for more detail on these and related subject areas, including the

- AASHTO Policy on Geometric Design of Highways and Streets,
- Manual on Uniform Traffic Control Devices,
- Manual of Traffic Signal Design,
- Traffic Detector Handbook, and
- Highway Capacity Manual.

Intersection Design Objectives and Considerations

As in all aspects of traffic engineering, intersection design has two primary objectives:

- To ensure safety for all users, including drivers, passengers, pedestrians, bicyclists, and others, and,
- To promote efficient movement of all users (motorists, pedestrians, bicyclists, etc.) through the intersection.

Achievement of both is not an easy task because safety and efficiency are often competing rather than mutually reinforcing goals.

In developing an intersection design, AASHTO [/] recommends that the following elements be considered:

- Human factors
- Traffic considerations
- Physical elements
- Economic factors
- Functional intersection area

Human factors must be taken into account. Thus intersection designs should accommodate reasonable approach speeds, user expectancy, decision and reaction times, and other user characteristics. Design should, for example, reinforce natural movement paths and trajectories, unless doing so presents a particular hazard.

Traffic considerations include provision of appropriate capacity for all user demands; the distribution of vehicle types and turning movements; approach speeds; and special requirements for transit vehicles, pedestrians, and bicyclists.

Physical elements include the nature of abutting properties, particularly traffic movements generated by these properties (parking, pedestrians, driveway movements, etc.).

They also include the intersection angle, existence and location of traffic control devices, sight distances, and specific geometric characteristics, such as curb radii.

Economic factors include the cost of improvements (construction, operation, maintenance), the effects of improvements on the value of abutting properties (whether used by the expanded right-of-way or not), and the effect of improvements on energy consumption.

Finally, intersection design must encompass the full functional intersection area. The operational intersection area includes approach areas that fully encompass deceleration and acceleration zones as well as queuing areas. The latter are particularly critical at signalized intersections.

A Basic Starting Point: Sizing the Intersection

One of the most critical aspects of intersection design is the determination of the number of lanes needed on each approach. This is not an exact science because the result is affected by the type of control at the intersection, parking conditions and needs, availability of right-of-way, and a number of other factors that are not always directly under the control of the traffic engineer. Further, considerations of capacity, safety, and efficiency all influence the desirable number of lanes. As is the case in most design exercises, there is no one correct answer, and many alternatives may be available that provide for acceptable safety and operation.

Unsignalized Intersections

Unsignalized intersections may be operated under basic rules of the road (no control devices other than warning and guide signs), or under STOP or YIELD control.

When totally uncontrolled, intersection traffic volumes are generally light, and there is rarely a clear "major" street with significant volumes involved. In such cases, intersection areas do not often require more lanes than on the approaching roadway. Additional turning lanes are rarely provided. Where high speeds and/or visibility problems exist, channelization may be used in conjunction with warning signs to improve safety.

The conditions under which two-way (or one-way at a T-intersection or intersection of one-way roadways) STOP or YIELD control are appropriate are treated in previous lecture. The existence of STOP- or YIELD-controlled approaches, however, adds some new considerations into the design process:

- Should left-turn lanes be provided on the major street?
- Should right-turn lanes be provided on the major street?
- Should a right-turn lane be provided on minor approaches?
- How many basic lanes does each minor approach require?

Most of these issues involve capacity considerations. For convenience, however, some general guidelines are presented here.

When left turns are made from a mixed lane on the major street, there is the potential for unnecessary delay to through vehicles that must wait while left-turners find a gap in the opposing major-street traffic. The impact of major-street left turns on delay to all major-street approach traffic becomes noticeable when left turns exceed 150 veh/h. This may be used as a general guideline indicating the probable need for a major street left-turn lane, although a value as low as 100 veh/h could be justified.

Right-turning vehicles from the major street do not have a major impact on the operation of STOP- or YIELD-controlled intersections. Although they do not technically conflict with minor-street movements when they are made from shared lanes, they may impede some minor-street movements when drivers do not clearly signal that they are turning or approach the intersection at high speed. When major-street right turns art made from an exclusive lane, their intent to turn is more obvious to minor-street drivers. Right-turn lanes for major-street vehicles can be easily provided where on-street parking is permitted. In such situations, parking may be prohibited for 100 to 200 feet from the STOP line, thus creating a short right-turn lane.

Most STOP-controlled approaches have a single lane shared by all minor-street movements. Occasionally, two lanes are provided. Any approach with sufficient demand to require three lanes is probably inappropriate for STOP control.

Approximate guidelines for the number of lanes required may be developed from the unsignalized intersection analysis methodology of the Highway Capacity Manual. Table.1 shows various combinations of minor-approach demand versus total crossing traffic on the major street, along with guidelines as to whether one or two lanes would be needed.

They are based on assumptions that

- All major-street traffic, is through traffic,
- All minor- approach traffic is through traffic, and
- Various impedances and other non-ideal characteristics reduce the capacity of a lane to about 80% of its original value.

The other issue for consideration on minor STOP controlled approaches is whether or not a right-turning lane should be provided. Because the right-turn movement at a STOP-controlled approach is much more efficient than crossing and let-turn movements, better operation can usually be accomplished by providing a right-turn lane. This is often as simple as banning parking within 200 feet of the STOP line, and it prevents right-turning drivers from being stuck in a queue when they could easily be executing their movements.

Where a significant proportion of the minor-approach traffic is turning right (>20%), provision of a right-turning lane should always be considered.

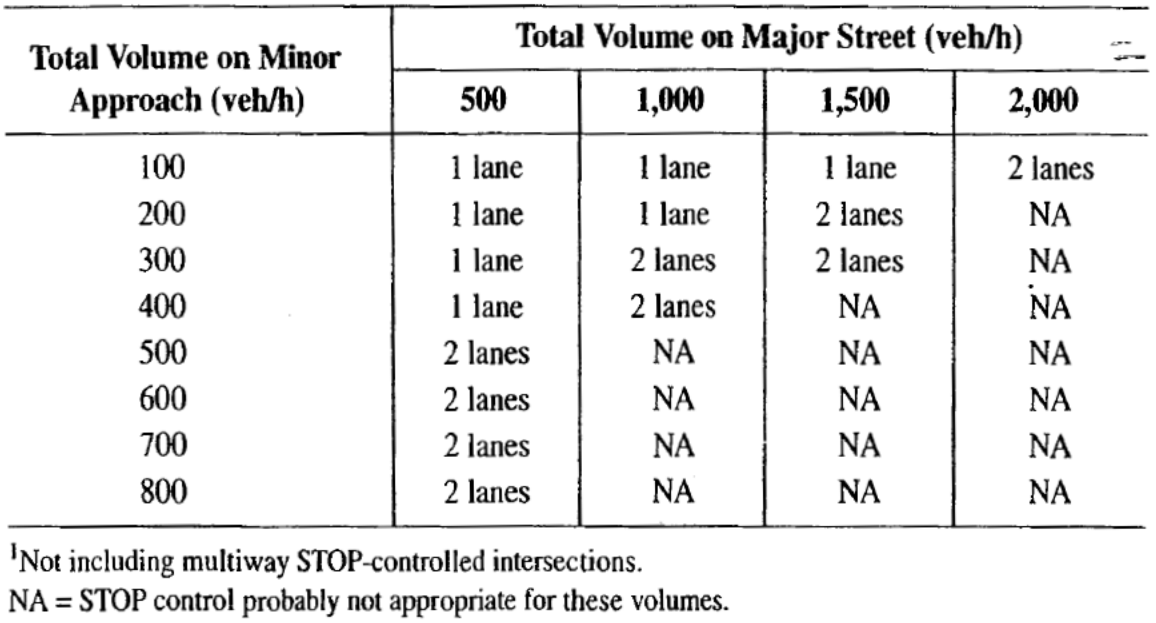
Note that the lane criteria of Table 1 are approximate. Any finalized design should be subjected to detailed analysis using the appropriate procedures of the HCM 2000 for the forthcoming HCM 2010).

Consider the following example: two-lane major road way carries a volume of 800 veh/h, of which 10% tum left and 5% turn right at a local street. Both approaches on the on local street are STOP-controlled and carry 150 veh/h, with 50 turning left and 50 turning right. Suggest an appropriate design for the intersection.

Given the relatively low volume of left turns (80/h) and right tums (40/h) on the major street, neither left- nor right turn lanes would be required, although they could be provided if space is available. From Table 1, it appears that one lane would be sufficient for each of the minor-street approaches.

The relatively heavy percentages of right turns (33%), however, suggests that a right-tum lane on each minor approach would be useful.

Table 1: Guidelines for Number of Lanes at STOP-Controlled Approaches



Total Volume on Minor Approach (veh/h)	Total Volume on Major Street (veh/h)			
	500	1,000	1,500	2,000
100	1 lane	1 lane	1 lane	2 lanes
200	1 lane	1 lane	2 lanes	NA
300	1 lane	2 lanes	2 lanes	NA
400	1 lane	2 lanes	NA	NA
500	2 lanes	NA	NA	NA
600	2 lanes	NA	NA	NA
700	2 lanes	NA	NA	NA
800	2 lanes	NA	NA	NA

[1] Not including multiway STOP-controlled intersections.
NA = STOP control probably not appropriate for these volumes.

Signalized Intersections

Approximating the required size and layout of a signalized intersection involves many factors, including the demands on each lane group, the number of signal phases, and the signal cycle length. Determining the appropriate number of lanes for each approach and lane group is not a simple design task. Like so many design tasks, there is no absolutely unique result, and many different combinations of physical design and signal timing can provide for a safe and efficient intersection. The primary control on number of lanes is the maximum sum of critical-lane volumes that the intersection can support.
This concept is more thoroughly discussed and illustrated in next lecture. The concept involves finding the single lane during a signal cycle that carries the most intense traffic, which means it would be the one that consumes the most green time of all movements to process its demand. Each signal phase has a critical-lane volume, and the cycle length of the signal is set to accommodate the sum of these critical volumes for each phase in the signal plan. This is the equation governing the maximum sum of critical-lane volumes:

$$V_c = \frac{1}{h}\left[3{,}600 - Nt_L\left(\frac{3{,}600}{C}\right)\right] \qquad (1)$$

Where:
V_c = maximum sum of critical-lane volumes, veh/h
h = average headway for prevailing conditions on the lane group or approach, s/veh
N = number of phases in the cycle

t_L = lost time per phase, s/phase
C = cycle length, s

Table 2 gives approximate maximum sums of critical-lane volumes for typical prevailing conditions. An average headway of 2.6 s/veh is used, along with a typical lost time per phase of 4.0 s (ti). Maximum sums are tabulated for a number of combinations of and C.

Consider the case of an intersection between two major arterials. Arterial 1 has a peak directional volume of 900 veh/h; Arterial 2 has a peak directional volume of 1,100 veh/h. Turning volumes are light, and a two-phase signal is anticipated. As a preliminary estimate, what number of lanes is needed to accommodate these volumes, and what range of cycle lengths might be appropriate?

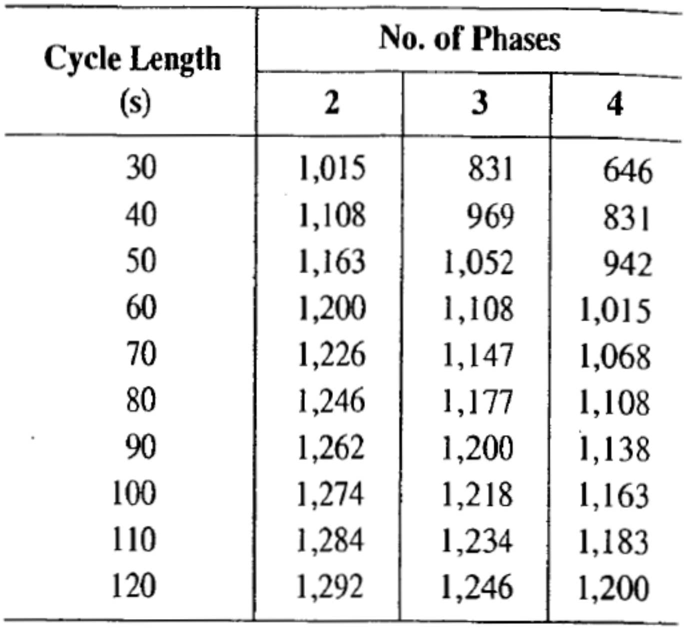
From Table 2, the range of maximum sums of critical lane volumes is between 1,015 veh/h for a 30-second cycle length and 1,292 veh/h for a 120-second cycle length. The two critical volumes are given as 900 veh/h and 1,100 veh/h. If only one lane is provided for each, then the sum of critical-lane volumes is

900 + 1,100 = 2,000 veh/h, well outside the range of maximum values for reasonable cycle lengths. Table 3 shows a number of reasonable scenarios for the number of lanes on each critical approach along with the resulting sum of critical-lane volumes.

With one lane on Arterial 1 and 3 lanes on Arterial 2, the sum of critical-lane volumes is 1,267 veh/h. From Table 2, this would be a workable solution with a cycle length over 100 seconds. With two lanes on each arterial, the sum of critical-lane volumes is 1,000 veh/h. This situation would be workable at any cycle length between 30 and 120 seconds. All other potentially workable scenarios in Table 19.3 could accommodate any cycle length between 30 and 120 seconds as well.

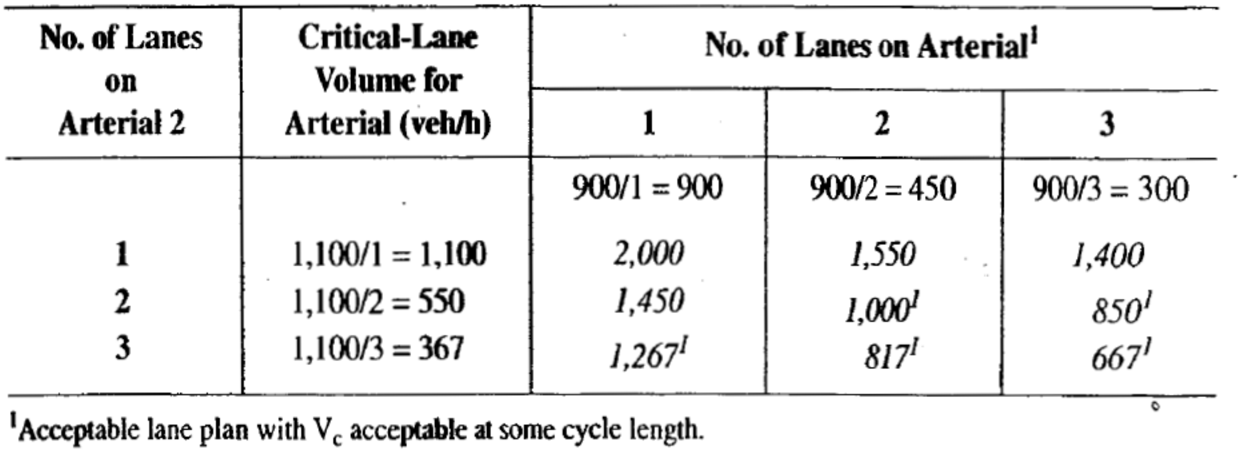
This type of analysis does not yield a final design or cycle length because it is approximate. But it does give the traffic engineer a basic idea of where to start. In this case, providing two lanes on each arterial in the peak direction appears to be a reasonable solution. Because peaks tend to be reciprocal (what goes one way in the morning conies back the opposite way in the evening), two lanes would also be provided for the off-peak directions on each arterial as well.

Table 2: Maximum Sums of Critical-Lane Volumes for a Typical Signalized Intersection.



Cycle Length (s)	No. of Phases		
	2	3	4
30	1,015	831	646
40	1,108	969	831
50	1,163	1,052	942
60	1,200	1,108	1,015
70	1,226	1,147	1,068
80	1,246	1,177	1,108
90	1,262	1,200	1,138
100	1,274	1,218	1,163
110	1,284	1,234	1,183
120	1,292	1,246	1,200

Table 3: Sum of Critical-Lane Volumes (veh/h) for Various Scenarios: Sample Problem



No. of Lanes on Arterial 2	Critical-Lane Volume for Arterial (veh/h)	No. of Lanes on Arterial[1]		
		1	2	3
		900/1 = 900	900/2 = 450	900/3 = 300
1	1,100/1 = 1,100	2,000	1,550	1,400
2	1,100/2 = 550	1,450	1,000[1]	850[1]
3	1,100/3 = 367	1,267[1]	817[1]	667[1]

[1] Acceptable lane plan with V_c acceptable at some cycle length.

The signal timing should then be developed using the methodology of HCM. The final design and timing should then be subjected to analysis using the Highway Capacity Manual (see Chapter 24) or some other appropriate analysis technique.

The number of anticipated phases is, of course, critical to a general analysis of this type. Suggested criteria for determining when protected left-tum phases are needed are given in next lecture. Because there is a critical-lane volume for each signal phase; a four-phase signal involves four critical-lane volumes, for example.

Exclusive left-tum lanes must be provided whenever a fully protected left-tum phase is used and is highly desirable w/hen compound left-tum phasing (protected + permitted or vice versa) is used.

Intersection Channelization

General Principles

Channelization can be provided through the use of painted markings or by installation of raised channelizing islands. The AASHTO Policy on Geometric Design of Highways and Streets [1] gives a number of reasons for considering channelization at an intersection:

- Vehicle paths may be confined so that no more than two paths cross at any one point.
- The angles at which merging, diverging, or weaving movements occur may be controlled.
- Pavement area may be reduced, decreasing the tendency to wander and narrowing the area of conflict between vehicle paths.
- Clearer indications of proper vehicle paths may be provided.
- Predominant movements may be given priority.
- Areas for pedestrian refuge may be provided.
- Separate storage lanes may be provided to permit turning vehicles to wait clear of through-traffic lanes.
- Space may be provided for the mounting of traffic control devices in more visible locations.
- Prohibited tums may be physically controlled.
- Vehicle speeds may be somewhat reduced.

The decision to channelize an intersection depends on a number of factors, including the existence of sufficient right-of-way to accommodate an effective design. Factors such as terrian, visibility, demand, and cost also enter into the decision. Channelization supplements other control measures but can sometimes be used to simplify other elements of control.

Some Examples

It is difficult to discuss channelization in the abstract. A selection of examples illustrates the implementation of the principles noted previously.

Figure 1 shows the intersection of a major street (E-W) with a minor crossroad (N-S). A median island is provided on the major street. Partial channelization is provided for the southbound (SB) right turn, and a left-tum lane is provided for the eastbound (EB) left turn. The two channelized tums are reciprocal, and the design reflects a situation in which these two turning movements are significant. The design illustrated minimizes the conflict between SB right tums and other movements and provides a storage lane for EB left turns, removing the conflict with EB through movements.

The lack of any channelization for other turning movements suggests they have light demand. The design does not provide for a great deal of pedestrian refuge, except for the wide median on the east leg of the intersection. This suggests that pedestrian volumes are relatively low at this location; if this is so, the crosswalk markings are optional. The channelization at this intersection is appropriate for both an unsignalized and a signalized intersection.

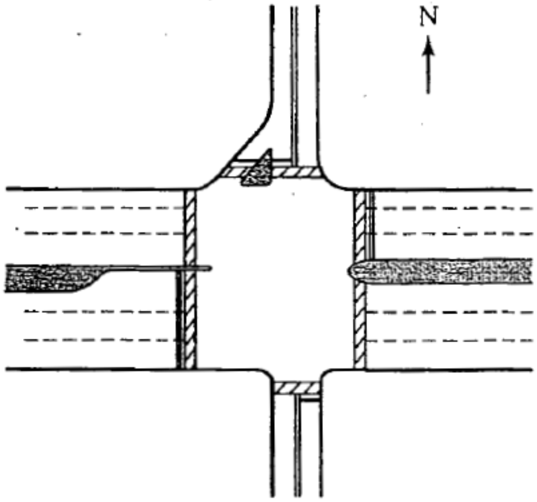


Figure 1: A Four-Leg Intersection with Partial Channelization for SB-EB and EB-SB Movements

Figure 2 shows a four-leg intersection with similar turning movements as in Figure 1. In this case, however, the SB-EB and EB-SB movements are far heavier and require a more dramatic treatment. Here channelization is used to create two additional intersections to handle these dominant tums. Conflicts between the various turning movements are minimized in this design.

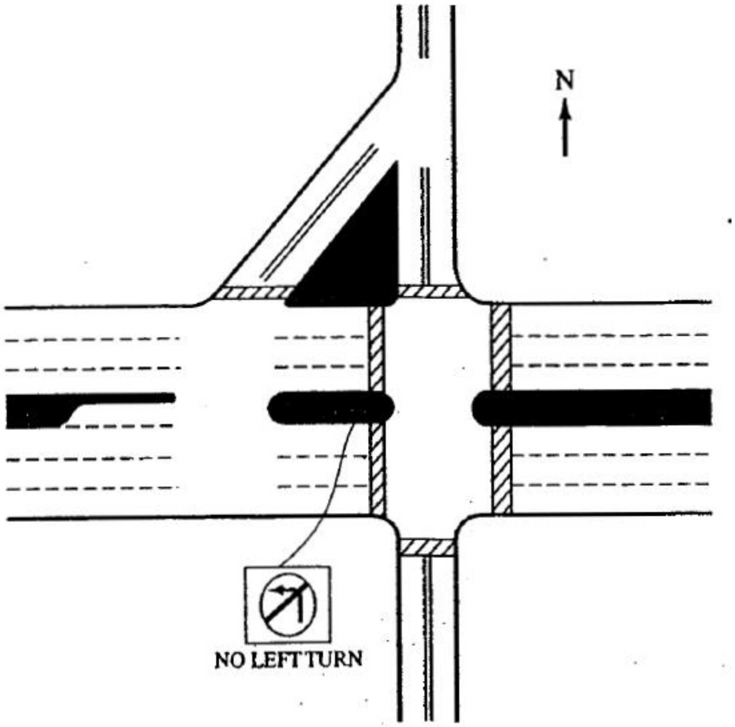


Figure 2: A Four-Leg Intersection Channelization for Major SB-EB and EB-SB Movements

Figure 3 is a similar four-leg intersection with far greater use of channelization. All right tums are channelized, and both major street left-turning movements have an exclusive left-turn lane. This design addresses a situation in which turning movements are more dominant. Pedestrian refuge is provided only on the right-turn channelizing islands, which may be limited by the physical size of the islands. Again, the channelization scheme is appropriate for either signalized or unsignalized control.

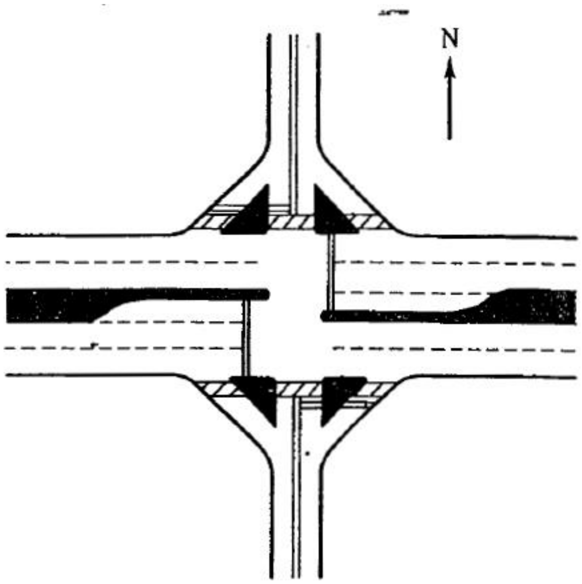


Figure 3: A Four-Leg Intersection with Full Channelization of Right Turns

Channelization can also be used at locations with significant traffic volumes to simplify and reduce the number of conflicts and to make traffic control simpler and more effective. Figure 4 illustrates such a case.

In this case, a major arterial is fed by two major generators, perhaps two large shopping centers, on opposite sides of the roadway. Through movements across the arterial are prevented by the channelization scheme as are left turns from either generator onto the arterial. The channelization allows only the following movements to take place:

- Through movements on the arterial
- Right-tum movements into either generator
- Left-tum movements into either generator
- Right-tum movements onto the arterial

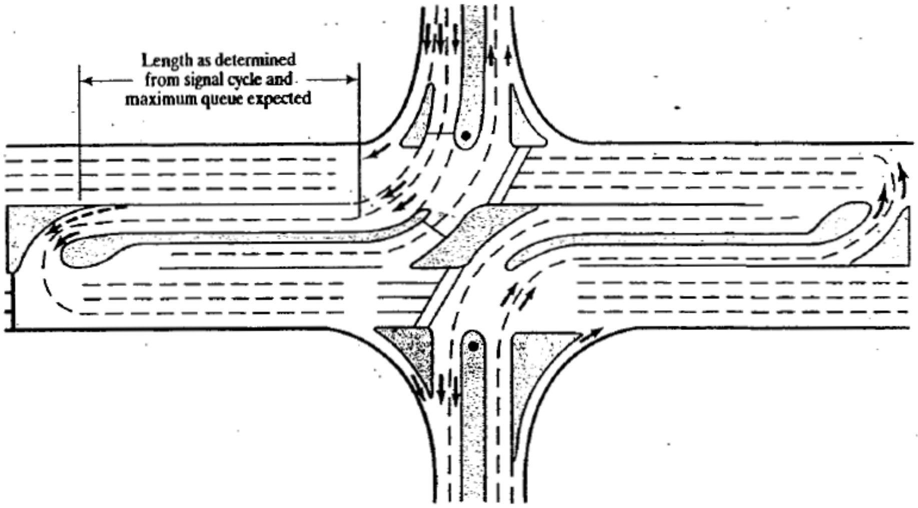


Figure 4: Channelization of a Complex Intersection

(Source: Used with permission of Institute of Transportation Engineers, R.P. Kramer, and "New Combination of Old Techniques to Rejuvenate Jammed Suburban Arterials," Strategies to Alleviate Traffic Congestion, Washington DC, 1988.).

Double-left-tum lanes on the arterial are provided for storage and processing of left turns entering either generator. A wide median is used to nest a double U-turn lane next to the left-tum lanes. These U-tum lanes allow vehicles to exit either generator and accomplish either a left-turning movement onto the arterial or a through movement into the opposite generator. In this case, it is highly likely the main intersection and the U-tum locations would be signalized. However, all movements at this complex location could be handled with two-phase signalization because the channelization design limits the signal to the control of two conflicting movements at each of the three locations. The distance between the main intersection and the U-tum locations must consider the queuing characteristics in the segments between intersections to avoid spill back and related demand starvation issues. From these examples, you can see that channelization of intersections can be a powerful tool to improve both the safety and the efficiency of intersection operation.

Channelizing Right Turns

When space is available, it is virtually always desirable to provide a channelized path for right-turning vehicles. This is especially true at signalized intersections where such channelization accomplishes two major benefits:

- Where "right-turn on red" regulations are in effect, channelized right turns minimize the probability of a right-turning vehicle or vehicles being stuck behind a through vehicle in a shared lane.
- Where channelized, right turns can effectively be removed from the signalization design because they would, in most cases, be controlled by a YIELD sign and would be permitted to move continuously.

The accomplishment of these benefits, however, depends on some of the details of the channelization design.

Figure 5 shows three different schemes for providing channelized right turns at an intersection. In Figure 5 (a), a simple channelizing triangle is provided.

This design has limited benefits for two reasons:

(1) Through vehicles in the right lane may queue during the "red" signal phase, blocking access to the channelized right-tum lane-and

(2) High right-turn volumes may limit the usefulness of the right-hand lane to through vehicles during "green" phases.

In the second design, shown in Figure 5 (b), acceleration and deceleration lanes are added for the channelized right turn. If the lengths of the acceleration and deceleration lanes are sufficient, this design can avoid the problem of queues blocking access to the channelized right tum.

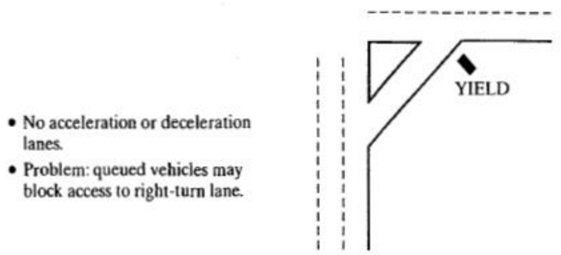
In the third design. Figure 5 (c), a very heavy right turn movement can run continuously. A lane drop on the approach leg and a lane addition to the departure leg provide a continuous lane and an unopposed path for right-turning vehicles.

This design requires unique situations in which the lane drop and lane addition are appropriate for the arterials involved. To be effective, the lane addition on the departure leg cannot be removed too close to the intersection. It should be carried for at least several thousand feet before it is dropped, if necessary.
Right-tum channelization can simplify intersection operations, particularly where the movement is significant. It can also make signalization more efficient because channelized right turns, controlled by a YIELD sign, do not require green time to be served.

Special Situations at Intersections

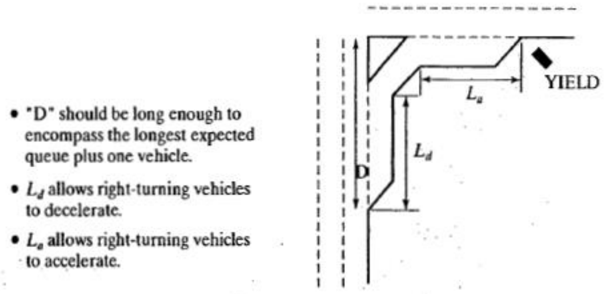
This section deals with four unique intersection situations that require attention:

- Intersections with junction angles less than 60° or more than 120°,
- T-intersections,
- Offset intersections, and
- Special treatments for heavy left-tum movements.



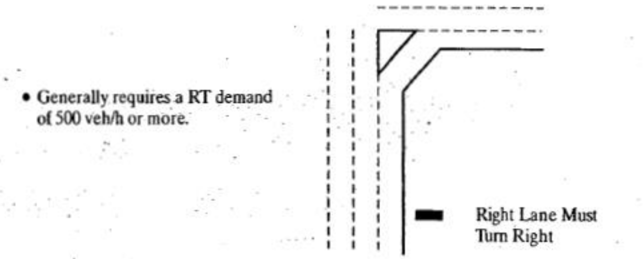
- No acceleration or deceleration lanes.
- Problem: queued vehicles may block access to right-turn lane.

(a) Simple Channelized Right Turn



- "D" should be long enough to encompass the longest expected queue plus one vehicle.
- L_d allows right-turning vehicles to decelerate.
- L_a allows right-turning vehicles to accelerate.

(b) Channelized Right Turn with Acceleration and Deceleration Lanes



- Generally requires a RT demand of 500 veh/h or more.

(c) Channelized Right Turn with Lane Drop and Lane Addition

Figure 3: Three Ways to Channelize a Right Turn.

Intersections at Skewed Angles

Intersections, both signalized and unsignalized, work best when (he angle of the intersection is 90°

- Sight distances are easier to define, and drivers tend to expect intersections at right angles. Nevertheless, in many situations the intersection angle is not 90°. Such angles may present special challenges to the traffic engineer, particularly when they are less than 60° or more don 120°
- These occur relatively infrequently. Drivers are generally less familiar with their special characteristics, particularly vis-a-vis sight lines and distances.

Skewed-angled intersections are particularly hazardous when uncontrolled and combined with high intersection approach speeds. Such cases generally occur in rural areas and involve primary state and/or county routes. The situation illustrated in Figure 6 provides an example.

The example is a rural junction of two-lane, high-speed arterials. Routes 160 and 190. Given relatively gentle terrain, low volumes, and the rural setting, speed limits of 50 mi/h are in effect on both facilities. Figure 6 also illustrates the two movements representing a hazard. The conflict between the WB movement on Route 160 and the EB movement on Route 190 is a significant safety hazard. At the junction shown, both roadways have similar designs. Thus there is no visual cue to the driver indicating which route has precedence or right-of-way. Given that signalization is rarely justifiable in low-volume rural settings, other means must be considered to improve the safety of operations at the intersection.

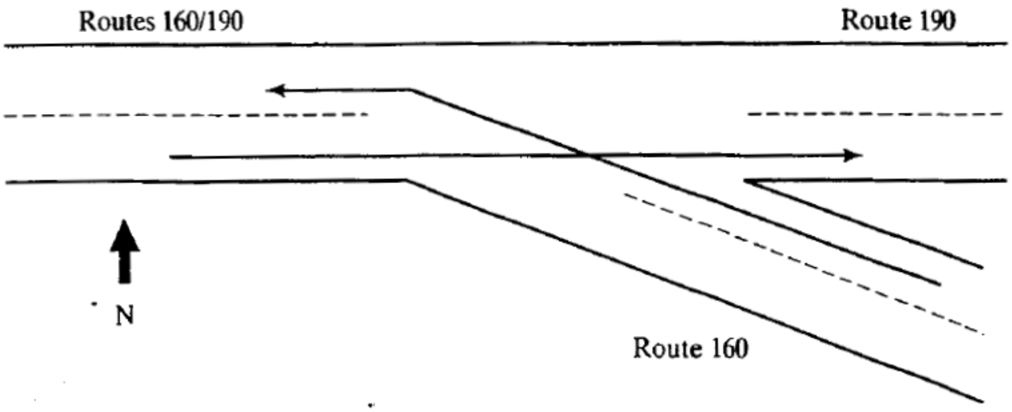


Figure 6: A Skewed-Angle Rural Intersection

The most direct means of improving the situation is to change the alignment of the intersection, making it clear which of the routes has the right-of-way. Figure 7 illustrates the two possible realignments. In the first case. Route 190 is given clear preference; vehicles arriving or departing on the east leg of Route 160 must go through a 90° intersection to complete their maneuver. In the second case. Route 160 is dominant, and those arriving or departing on the east leg of Route 190 go through the 90° intersection. In either case, the 90° intersection would be controlled using a STOP sign to clearly designate right-of-way.

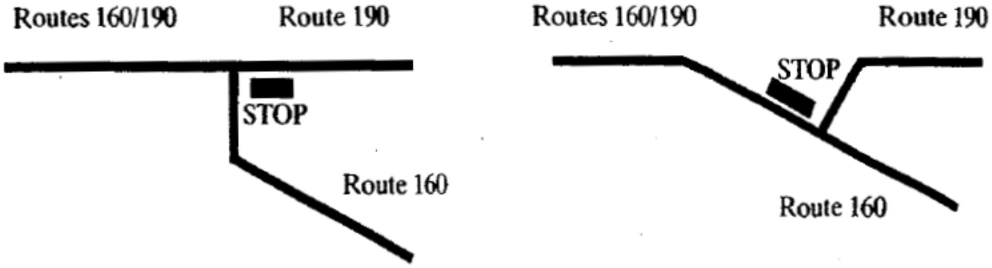


Figure 7: Potential Realignment for Rural Intersection

Although basic realignment is the best solution for high speed odd-angle intersections, it requires that right-of-way be available to implement the change. Even in a rural setting, sufficient right-of-way to realign the intersection may not always be available. Other solutions can also be considered. Channelization can be used to better define the intersection movements, and control devices can be used to designate right-of-way.

Figure 8 shows another potential design that requires less right-of-way than full realignment.

In this case, only the WB movement on Route 106 was realigned. Although this would still require some right-of-way, the amount needed is substantially less than for full realignment.

Additional channelization is provided to separate EB movements on Routes 106 and 109. In addition to the regulatory signs indicated in Figure 8, warning and directional guide signs would be placed on all approaches to the intersection.

In this solution, the WB left turn from Route109 must be prohibited; an alternative route would have to be provided and appropriate guide signs designed and placed.

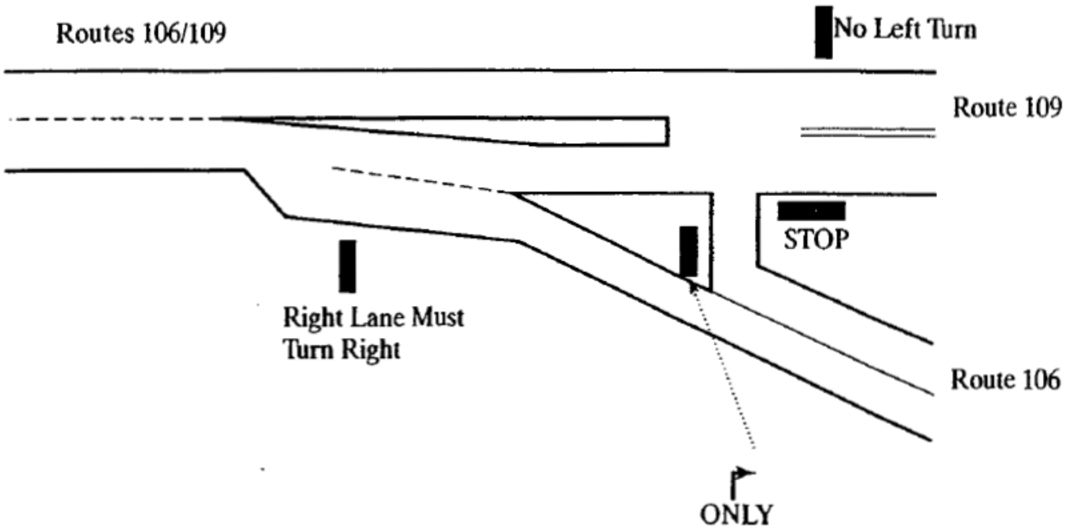


Figure 8: An Alternative Solution Using Channelization

The junction illustrated is, in essence, a three-leg intersection. Skewed-angle four-leg intersections also occur in rural, suburban, and urban settings and present similar problems.

Again, total realignment of such intersections is the most desirable solution. Figure 9 shows an intersection and the potential realignments that would eliminate the odd-angle junction. Where a four-leg intersection is involved, however, the realignment solution creates two separate intersections. Depending on volumes and the general traffic environment of the intersection, the realignments proposed in Figure 9 could result in signalized or unsignalized intersections.

In urban and suburban settings, where right-of-way is a significant impediment to realigning intersection, signalization of the odd-angle intersection can be combined with channelization to achieve safe and efficient operations. Channelized right turns would be provided for acute-angle turns, and left turn lanes (and signalization) would be provided as needed.

In extreme cases, where volumes and approach speeds present hazards that cannot be ameliorated through normal traffic engineering measures, consideration may be given to providing a full or partial interchange with the two main roadways grade-separated. Providing grade separation would also involve some expansion of the traveled way, and overpasses in some suburban and urban surroundings may involve visual pollution and/or other negative environmental impacts.

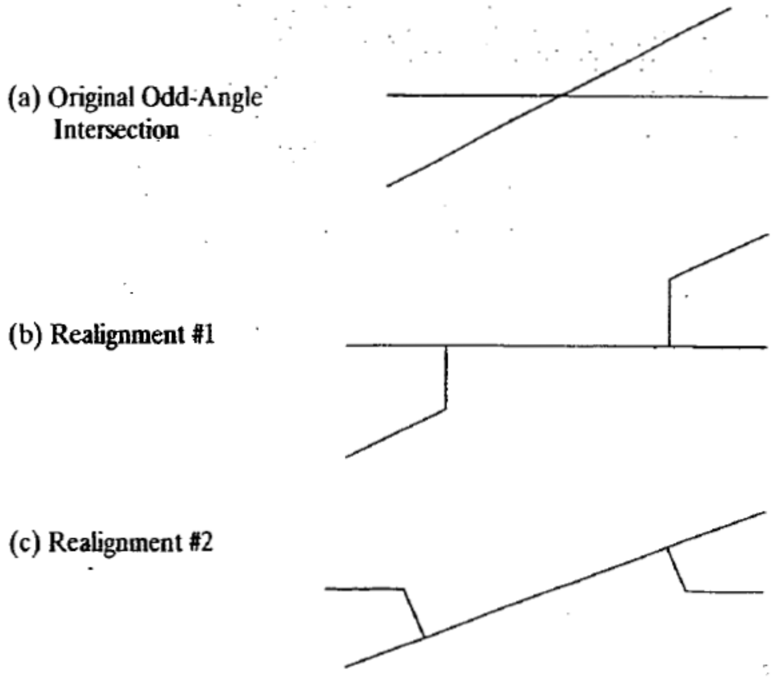


Figure 9: Realignment of Four-Leg Odd-Angle Intersections

T-intersections: Opportunities for Creativity

In many ways, T-intersections are far simpler than traditional four-leg intersections. The typical four-leg intersection contains 12 vehicular movements and 4 crossing pedestrian movements.

At a T-intersection, only six vehicular movements exist and there are only three crossing pedestrian movements. These are illustrated in Figure 10.

Note that in the set of T-intersection vehicular movements, there is only one opposed left turn-the WB left-turn movement in this case. Because of this, conflicts are easier to manage, and signalization, when necessary, is easier to address.

Control options include all generally applicable alternatives for intersection control:

- Uncontrolled (warning and guide signs only)
- STOP or YIELD control
- Signal control

The intersection shown in Figure 10 has one lane for each approach. There are no channelized movements or left-turn lanes. If visibility is not appropriate for uncontrolled operation under basic rules of the road, then the options of STOP/YIELD control or signalization must be considered. The normal warrants would apply.

The T-intersection form, however, presents some relatively unique characteristics that influence how control is applied. STOP-control is usually applied to the stem of the T-intersection, although it is possible to apply two-way STOP control to the cross street if movements into and out of the stem dominate.

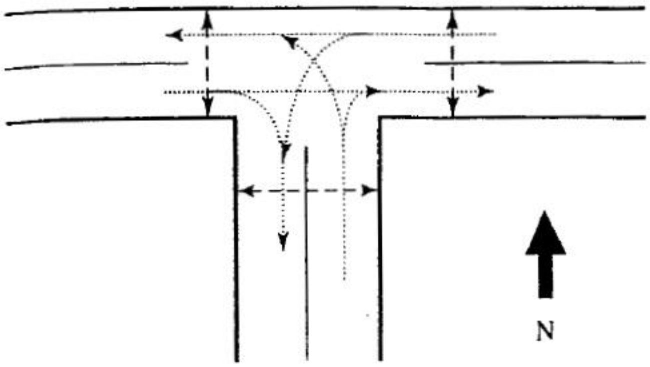
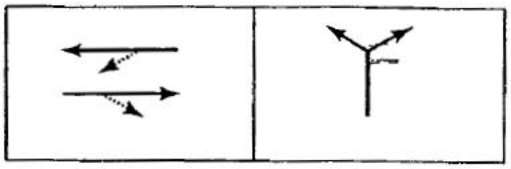


Figure 10: Simple T-Intersection Illustrated

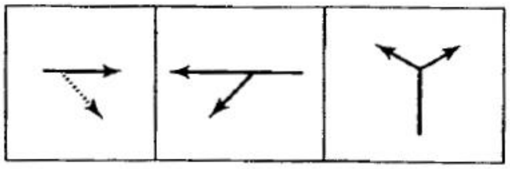
If needed, the form of signalization applied to the intersection of Figure 10 depends entirely on the need to protect the (WB) opposed left turn. A protected phase is normally suggested if the left-turn volume exceeds 200 veh/h or the cross-product of the left turn volume and the opposing volume per lane exceeds 50,000. If left-turn protection is not needed, a simple two-phase signal plan is used. If the opposed left-turn must be protected and there is no left-turn lane available (as in Figure 10), a three-phase plan must be used.

Figure 11 illustrates the possible signal plans for the T-intersection of Figure 10. The three-phase plan is relatively inefficient because a separate phase is needed for each of the three approaches.

Where a protected left-turn phase is desirable, the addition of an exclusive left-turn lane would simplify the signalization. Channelization and some additional right-of-way would be required to do this. Channelization can also be applied in other ways to simplify the overall operation and control of the intersection. Channelizing islands can be used to create separated right-turn paths for vehicles entering and leaving the stem via right turns. Such movements would be YIELD-controlled, regardless of the primary form of interaction control.



(a) A Two-Phase Signal Plan for the T-Intersection of Figure 19.10 (Permitted Left Turns)



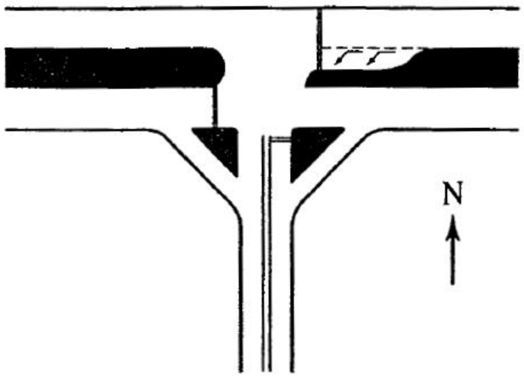
(b) A Three-Phase Signal Plan for the T-Intersection of Figure 19.10 (Protected Left Turns)

Figure 11: Signalization Options for the T-Intersection of Figure 10

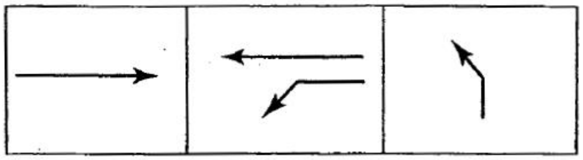
Figure 12 shows a T-intersection in which a left turn lane is provided for the opposed left turn. Right turns are also channelized. Assuming that a signal with a protected left turn is needed at this location, the signal plan shown could be implemented. This plan is far more efficient than that of Figure 11 because EB and WB through flows can move simultaneously. Right turns move more or less continuously through the YIELD-controlled channelized turning roadways.

The potential for queues to block access to the right turn roadways, however, should be considered in timing the signal.

Right turns can be completely eliminated from the signal plan if volumes are sufficient to allow lane drops or additions for the right-turning movements, as illustrated in Figure 13, Right turns into and out of the stem of the T-intersection become continuous movements.



(a) A Channelized T-Intersection



(b) Signal Plan with Protected Left Turn and YIELD-Controlled Right Turns

Figure 12: A Channelized T-Intersection with Improved Signalization

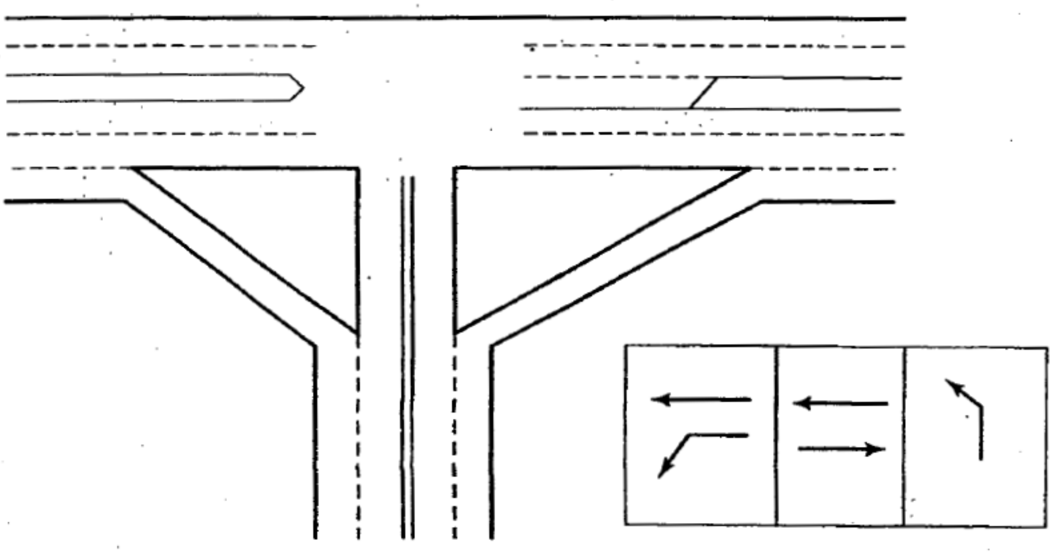


Figure 13: T-Intersection and Signal Plan with Right-Turn Lane Drops and Lane Additions

Offset Intersections

One of the traffic engineer's most difficult problems is the safe operation of high-volume offset intersections. Figure 14 illustrates such an intersection with a modest right offset. In the case illustrated, the driver needs more sight distance (when compared with a perfectly aligned 90° intersection) to observe vehicles approaching from the right. The obstruction caused by the building becomes a more serious problem because of this. In addition to sight-distance problems, the offset intersection distorts the normal trajectory of all movements, creating accident risks that do not exist at aligned intersections.

Offset intersections are rarely consciously designed. They are necessitated by a variety of situations, generally involving long-standing historic development patterns.

Figure 15 illustrates a relatively common situation in which offset intersections occur. In many older urban or suburban developments, zoning and other regulations were (and in some cases, still are) not particularly stringent. Additional development was considered to be an economic benefit because it added to the property tax base of the community involved. Firm control over the specific design of subdivision developments, therefore, is not always exercised by zoning boards and authorities. The situation depicted in Figure 15 occurs when Developer A obtains the land" to the south of a major arterial and lays out a circulation system that will maximize the number of building lots that can be accommodated on the parcel. At a later time. Developer B obtains the rights to land north of the same arterial. Again, an internal layout that provides the maximum number of development parcels is selected. Without a strong planning board or other oversight group requiring it, there is no guarantee that opposing local streets will "line up." Offsets can and do occur frequently in such circumstances. In urban and suburban environments, it is rarely possible to acquire sufficient right-of-way to realign the intersections; therefore, other approaches to control and operation of such intersections must be considered. Two major operational problems are posed by a right-offset intersection, as illustrated in Figure 16. In Figure 16 (a), the left-turn trajectories from the offset legs involve a high level of hazard. Unlike the situation with an aligned intersection, a vehicle turning left from either offset leg is in conflict with the opposing through vehicle almost immediately after crossing the STOP line. To avoid this conflict, left-turning vehicles must bear right as if they were going to go through to the opposite leg, beginning their left turns only when they are approximately halfway through the intersection. This, of course, is not a natural movement, and a high incidence of left-turn accidents often result at such intersections.

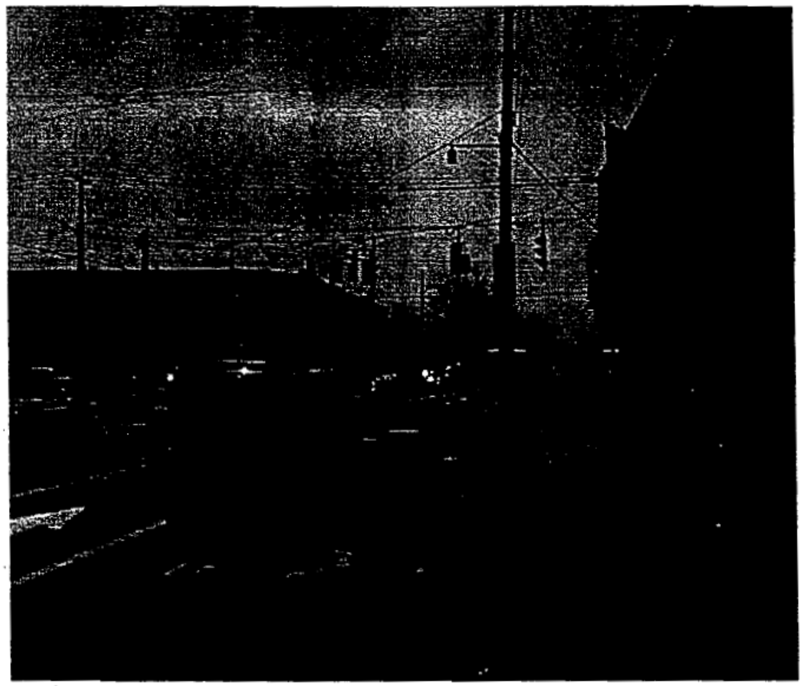


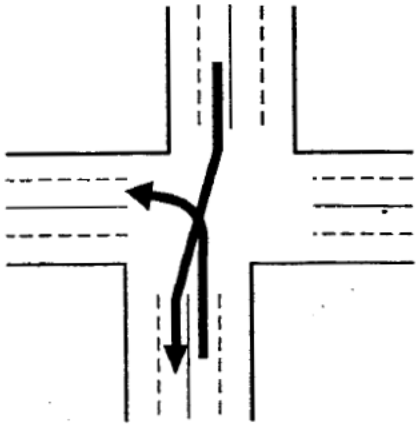
Figure 14: Offset Intersection with Sight Distance and Trajectory Problems

In Figure 16 (b), the hazard to pedestrians crossing the aligned roadway is highlighted. Two paths are possible, and both are reasonably intuitive for pedestrians: They can cross from corner to comer, following an angled crossing path, or they can cross perpendicularly. The latter places one end of their crossing away from the street comer. Perpendicular crossings, however, minimize the crossing time and distance. However, right-turning vehicles encounter the pedestrian conflict at an unexpected location, after they have virtually completed their right turn. Diagonal crossings increase the exposure of pedestrians, but conflicts with right-turning vehicles are closer to the normal location.

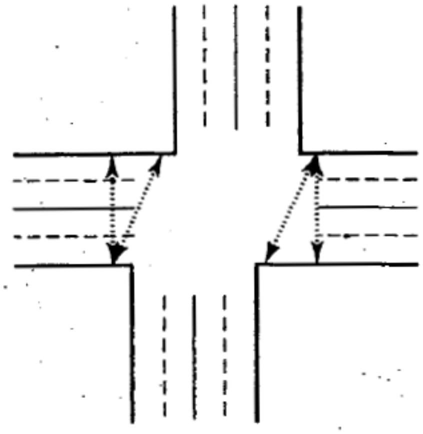
Yet another special hazard at offset intersections, not clearly illustrated by Figure 16, is the heightened risk of sideswipe accidents as vehicles cross between the offset legs. Because the required angular path is not necessarily obvious, more vehicles will stray from their lane during the crossing.

There are, however, remedies that will minimize these additional hazards. Where the intersection is signalized, the left-tum conflict can be eliminated through the use of a fully protected left-tum phase in the direction of the offset.

In this case, the left-turning vehicles will not be entering the intersection area at the same time as die opposing through vehicles. This requires, however, that one of the existing lanes be designated an exclusive turning lane or that a left-turn lane can be added to each offset leg. If this is not possible, a more extreme remedy is to provide each of the offset legs with an exclusive signal phase. Although this separates the left-turning vehicles from the opposing flows it is an inefficient signal plan and can lead to four-phase signalization if left-tum phases are needed on the aligned arterial.



(a) Left-Turn Trajectory Problems Illustrated

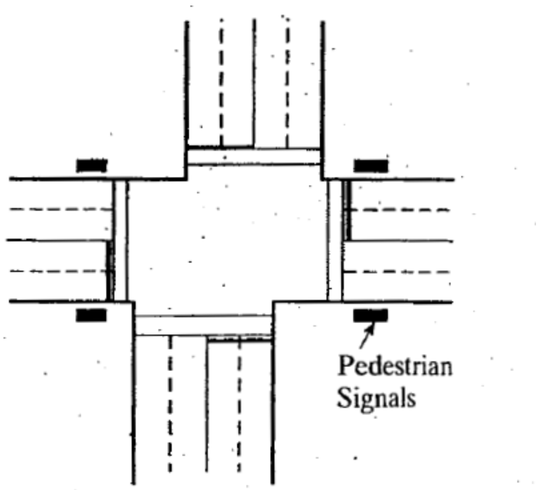


(b) Pedestrian Path Problems Illustrated

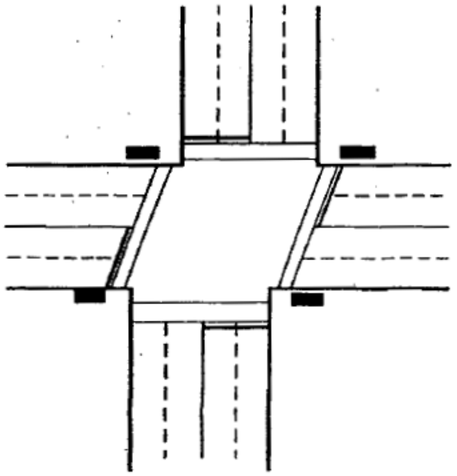
Figure 16: Special Problems at Offset Intersections

For pedestrian safety, it is absolutely necessary that the traffic engineer clearly designate the intended path they are to take. This is done through proper use of markings, signs, and pedestrian signals, as shown in Figure 17.

Crosswalk locations influence the location of ST0Plines and the position of pedestrian signals, which must be located in the line of sight (which is the walking path) of pedestrians. Vehicular signal timing is also influenced by the crossing paths implemented. Where perpendicular crossings are used, the distance between STOP-lines on the aligned street can be considerably longer than for diagonal crossings.



(a) Markings for Perpendicular Pedestrian Crossings



(b) Markings for Diagonal Pedestrian Crossings

Figure 17: Signing, Markings, and Pedestrian Signals for a Right-Offset Intersection

This increases the length of the all-red interval for the Signed Street and adds lost time to die signal cycle.

In extreme cases, where enforcement of perpendicular crossings becomes difficult, barriers can be placed at normal street comer locations, preventing pedestrians from entering the street at an inappropriate or unintended location.

To help vehicles follow appropriate paths through the offset intersection, dashed lane and centerline markings through the intersection may be added, as illustrated in Figure 18.

The extended centerline marking would be yellow, and the lane lines would be white. Left-offset intersections share some of the same problems as right-offset intersections. The left-turn interaction with the opposing through flow is not as critical, however. The pedestrian-right-turn interaction is different but potentially just as serious. Figure 19 illustrates the left-turn trajectory through the offset intersection is still quite different from an aligned intersection, but the left-turn movement does not thrust the vehicle immediately into the path of the oncoming through movement, as in a right-offset intersection. Sideswipe accidents are still a risk, and extended lane markings would be used to minimize this risk.

At a left-offset intersection, the diagonal pedestrian path is more difficult because it brings the pedestrian into immediate conflict with right-turning vehicles more quickly than at an aligned intersection. For this reason, diagonal crossings are generally not recommended at left-offset intersections.

The signing, marking, and signalization of perpendicular pedestrian crossings" is similar to that used at a right-offset intersection.

When at all possible, offset into sections should be avoided. If sufficient right-of-way is available, basic realignment should be seriously considered. When confronted with such a situation, however, the traffic engineering approaches discussed here can ameliorate some of the fundamental concerns associated with onset alignments. The traffic engineer should recognize that many of these measures will negatively affect capacity of the approaches due to the additional signal phases and longer lost times often involved. This is, however, a necessary price paid to optimize safety of intersection operation.

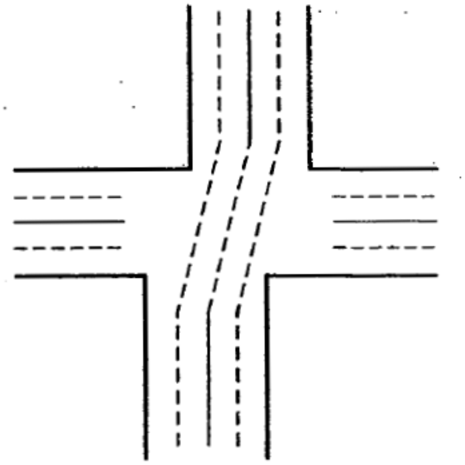


Figure 18: Dashed Lane and Centerline through an Offset Intersection

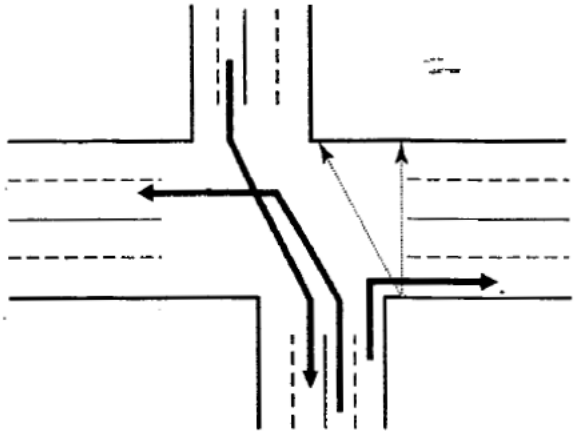


Figure 19: Conflicts at a Left-Offset Intersection

Special Treatments for Heavy Left-Turn Movements

Some of the most difficult intersection problems to solve involve heavy left-turn movements on major arterials. Accommodating such turns usually requires the addition of protected left-turn phasing, which often reduces the effective capacity to handle through movements. In some cases, adding an exclusive left turn phase or phases is not practical, given the associated losses in through capacity.

Alternative treatments must be sought to handle such left-tum movements, with the objective of maintaining two phase signalization at the intersection. Several design and control treatments are possible, including:

- Prohibition of left turns
- Provision of jug-handles
- Provision of at-grade loops and diamond ramps
- Provision of a continuous-flow intersection
- Provision of U-tum treatments

Prohibition of left turns is rarely a practical option for a heavy left-turn demand. Alternative paths would be needed to accommodate the demand for this movement, and diversion of a heavy flow onto an "around-the-block" or similar path often creates problems elsewhere.

Figure 20 illustrates the use of jug-handles for handling left turns. In effect, left-turners enter a surface ramp on the right, executing a left turn onto the cross street.

The jug-handle may also handle right-turn movements. The design creates two new intersections. Depending on volumes, these may require signalization or could be controlled with STOP signs. In either case, queuing between the main intersection and die two new intersections is a critical issue. Queues should not block egress from either of the jug-handle lanes.

The provision of jug-handles also requires sufficient right-of-way available to accommodate the solution. In some extreme cases, existing local streets may be used to form a jug-handle pattern.

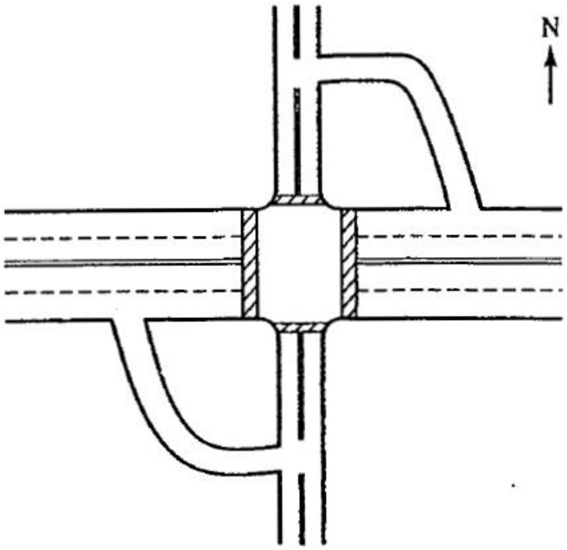


Figure 20: Jug-Handle Design for Left-Turning Vehicles

Figure 21 illustrates the use of surface loop ramps to handle heavy left-turning movements at an arterial intersection.
These are generally combined with surface diamond ramps to handle right turns from the cross street, thus avoiding the conflict between normal right turns and the loop ramp movements on the arterial. Once again, queuing could become a problem if left-turning vehicles back up along the loop ramp far enough to effect the flow of vehicles that can enter the loop ramp. This option also consumes considerable right-of-way and may be difficult to implement in high-density environments.

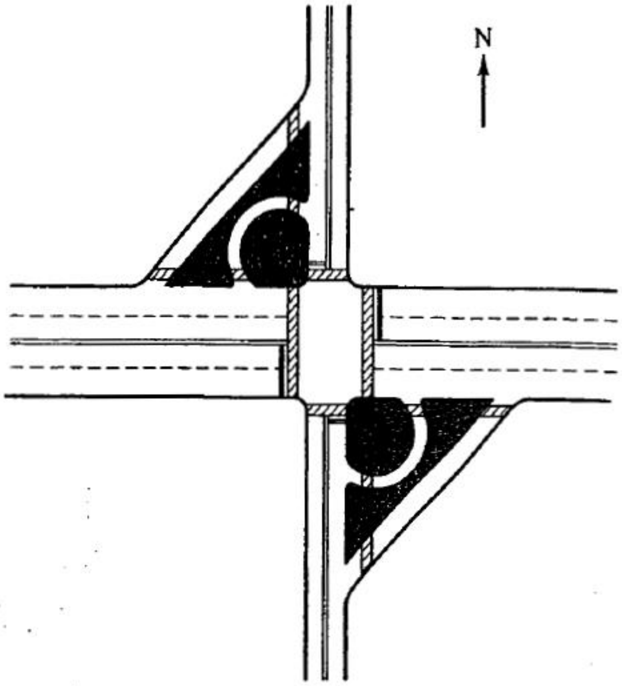


Figure 21: Surface Loop Ramp Design for Left Turns

Figure 22 illustrates a continuous-flow intersection, a relatively novel design approach developed during the late 1980s and early 1990s. The continuous-flow intersection [6] takes a single intersection with complex multiphase signalizations and separates it into two intersections, each of which can be operated with a two-phase signal and coordinated. At the new intersection, located upstream of the left-turn location, left-turning vehicles are essentially transferred to a separate roadway on the left side of the arterial. At the main intersection, the left turns can then be made without a protected phase, regardless of the demand level. The design requires sufficient right-of-way on one side of the arterial to create the new left-turn roadway and a median that is wide enough to provide one or two left-turning lanes at the new intersection. Queuing from the main intersection can become a problem if left-turning vehicles are blocked from entering the left-turn lane(s) at the new upstream intersection.

Although a few continuous-flow intersections have been built, they have not seen the widespread use that was originally anticipated. In most cases, right-of-way restrictions make this solution somewhat impractical.

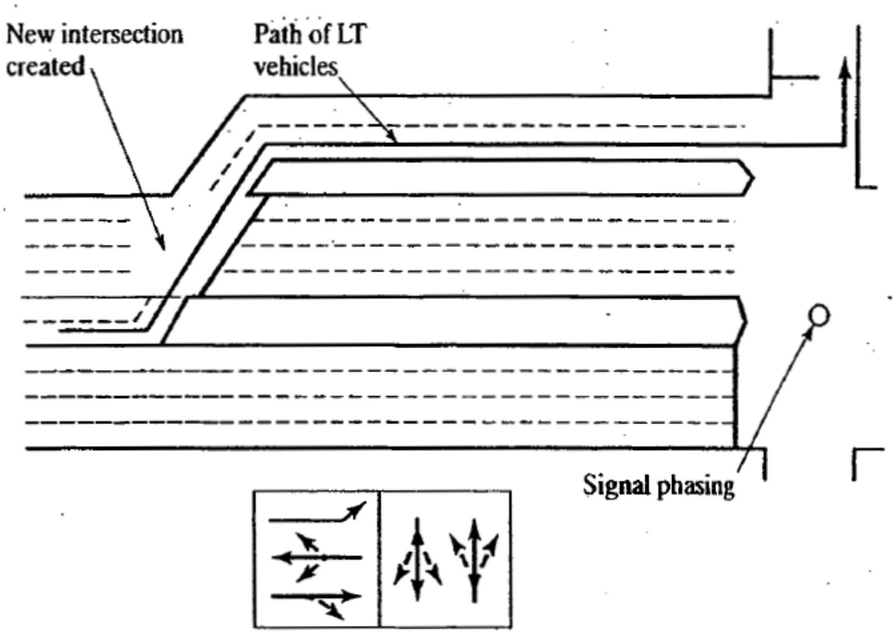
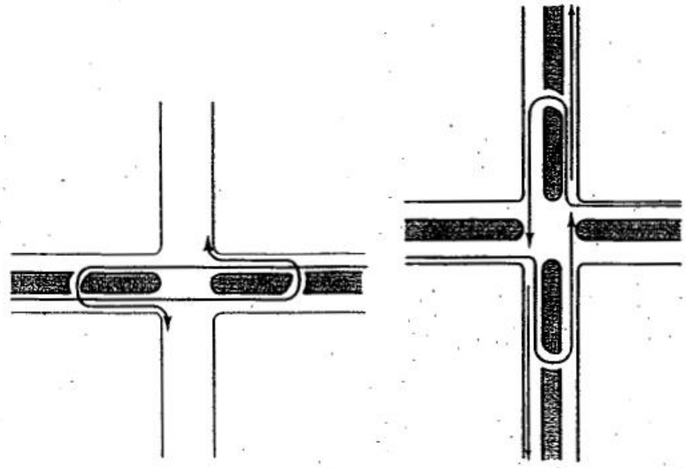


Figure 22: A Continuous Flow Intersection

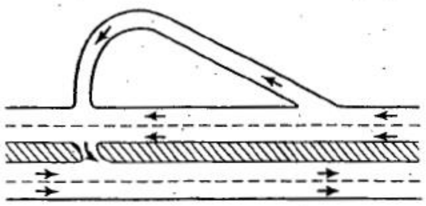
As a last resort, left turns may be handled in a variety of ways as U-turn movements. Figure 23 illustrates four potential designs for doing this. In Figure 23 (a), left turning vehicles go through the intersection and make a U-tum through a wide median downstream. The distance between the U-tum location and the main intersection must be sufficient to avoid blockage by queued vehicles and must provide sufficient distance for drivers to execute the required number of lane changes to get from the median lane to right lane. In Figure 23 (b), left-turning vehicles turn right at the main intersection, then execute a U-tum on the cross street. Queuing and lane-changing requirements are similar to those described for Figure 23 (a). Where medians are narrow, the U-tum paths of (a) and (b) cannot be provided. Figures 23 (c) and (d) use U-tum roadways built to the right and left sides of the arterial (respectively) to accommodate left-tuning movements. These options require additional right-of-way.

The safe and efficient accommodation of heavy left-tum movements on arterials often requires creative approaches that combine both design and control elements. The examples shown here are intended to be illustrations, not a complete review of all possible alternatives.

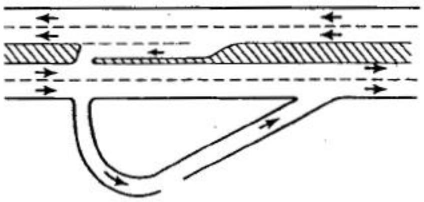


(a) Left turns handled as U-turns on the primary arterial.

(b) Left turns handled as U-turns on the cross street.



(c) Left turns handled as U-turns using a right-side U-turn roadway.



(d) Left turns handled as U-turns using a left-side U-turn roadway.

Figure 23: Left Turn Options Handled as U-Tums

Street Hardware for Signalized intersections

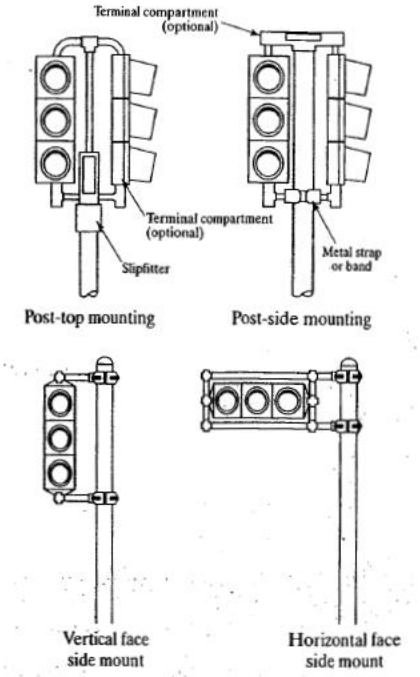
The basic requirements for display of signal faces at a signalized intersection were discussed in detail. These are the key specifications:

- A minimum of two signal faces should be visible to each primary movement in the intersection.

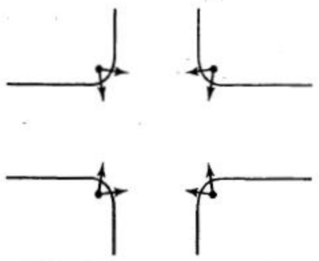
- All signal faces should be placed within a horizontal 20° angle around the centerline of the intersection approach (including exclusive left- and/or right-turn lanes).
- All signal faces should be placed at mounting heights in conformance with MUTCD standards.

The proper location of signal heads is a key element of intersection design and critical to maximizing observance of traffic signals. Three general types of signal-head mountings can be used alone or in combination to achieve the appropriate location of signal heads: post-mounting, mast-arm mounting, and span-wire mounting.

Figure 24 illustrates post-mounting. The signal head can be oriented either vertically or horizontally, as shown Post-mounted signals are located on each street corner. A post-mounted signal head generally has two faces, oriented such that a driver sees two faces located on each of the far intersection comers. Because they are located on street comers, care must be taken to ensure that post-mounted signals fall within the required 20° angle of the approach centerline. Post-mounted signals are often inappropriate for use at intersections with narrow streets because street comers in such circumstance lie outside of the visibility requirement.



(a) Post-mounting alternatives

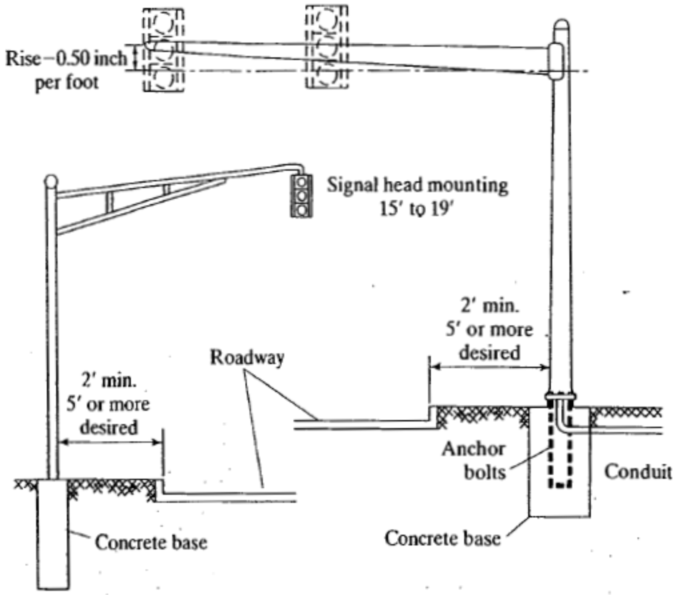


(b) Standard post-mounting locations

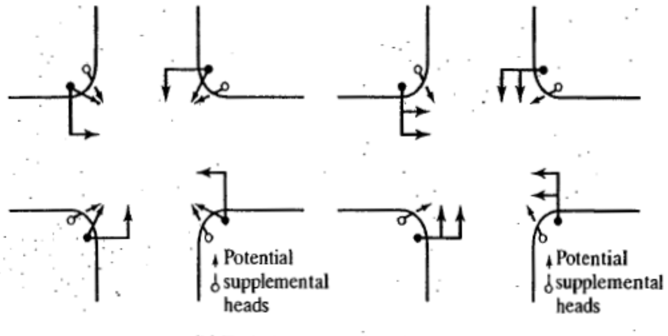
Figure 24: Post-Mounting of Signal Heads

{Source: Used with permission of Prentice-Hail Inc, Kell, Jand Fullerton, I., Manual of Traffic Signal Design, 2nd Edition, 1991. p. 44.)

Figure 25 illustrates mast-arm mounting of signal heads. Typically, the mast arm is perpendicular to the intersection approach. They are located so that drivers are looking at a signal face or faces on the far side of the intersection. Mast arms can be long enough to accommodate two signal heads, but they are rarely used for more than two signal heads.



(a) Mast-arm assemblies



(b) Typical mast-arm locations

Figure 25: Mast-Arm Mounting of Signal Heads
(Source: Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., Manual of Traffic Signal Design, 2nd Edition, 1991, p. 57.)

Figure 26 shows two typical mast-arm signal installations. The first (a) shows mast-arm signals at a four-leg intersection, with the mast-arm oriented perpendicular to the direction of traffic. Note that the mast-arm signal heads are supplemented by a post-mounted signal in the gore of the four-leg intersection. The second (b) represents a very efficient scheme for mounting signal heads at a simple intersection of two two-lane streets. Two mast arms are used, each extending diagonally across the intersection. Only two signal heads are used, each with a full four faces. In this way, using only two signal heads, all movements have two signal faces displaying the same signal interval.

In the case of both post-mounted and mast-arm-mounted signal heads, power lines are carried to the signal head within the hollow structure of the post or mast arm.

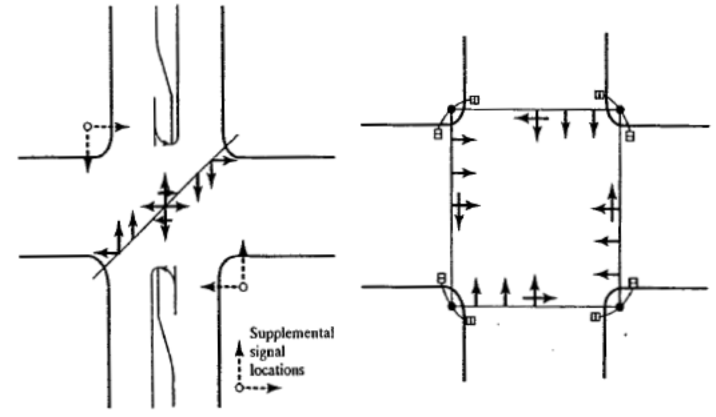
(a) Mast-Arm Mounted Signals at a Y-Intersection

(b) Mast-Arm Mounted Signals at the Intersection of Two 2-Lane Streets

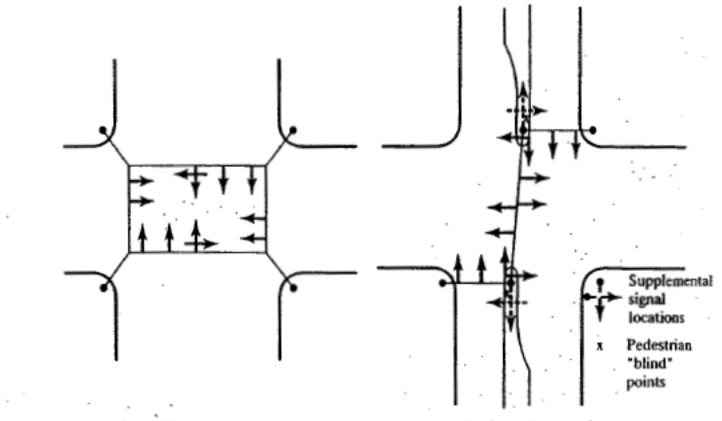
Figure 26: Two Examples of Mast-Arm Mounted Signals

The most common method for mounting signal heads is span wire because it is the most flexible and can be used in a variety of configurations. Figure 27 shows four basic configurations in which span wires can be used. The first is a single diagonal span wire between two intersection corners. The span wire allows the installation of a number of signal heads, each having between one and three faces, depending on the exact location. Such installations are generally supplemented by post-mounted signals on the two other intersection comers. The second installation illustrated is a "box" design. Four span wires are installed across each intersection leg. Signal heads are oriented much in the same way as with mast arms. Most signal heads have a single face and are visible from the far side of the intersection. The third example is a "modified box," in which the box is suspended over the middle of the intersection. This is done to accomplish signal-face locations that are more visible and more clearly aligned with specific lanes of each intersection approach.

The final example of Figure 27 is a "lazy Z pattern in which the primary span wire is anchored on opposing medians. This latter design is possible only where opposite medians exist.
Span wire allows the traffic engineer to place signal faces in almost any desired position and is often used at complex intersections where a signal face for each entering lane is desired.



Simple two-pole span with left-turn display Simple box span with left-turn display



Modified box span Typical Z-span

Figure 27: Span-Wire Mounting of Signal Heads.
(Source: Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., Manual of Traffic Signal Design, 2nd Edition, 1991, pp. 51 -53.).

Figure 28 illustrates how signal heads are anchored on span wires. In general, the main cable supports each signal head from above. Signal heads so mounted can and do sway in the wind. Where wind is excessive or where the exact orientation of the signal face is important, a tether wire may be attached to the bottom of the signal head 'or restraint. This is most important where Polaroid signal lenses are used. These lenses are visible only when viewed from a designated angle. They are often used at closely spaced signalized intersections, where the traffic engineer uses them to prevent drivers from reacting to the next downstream signal.

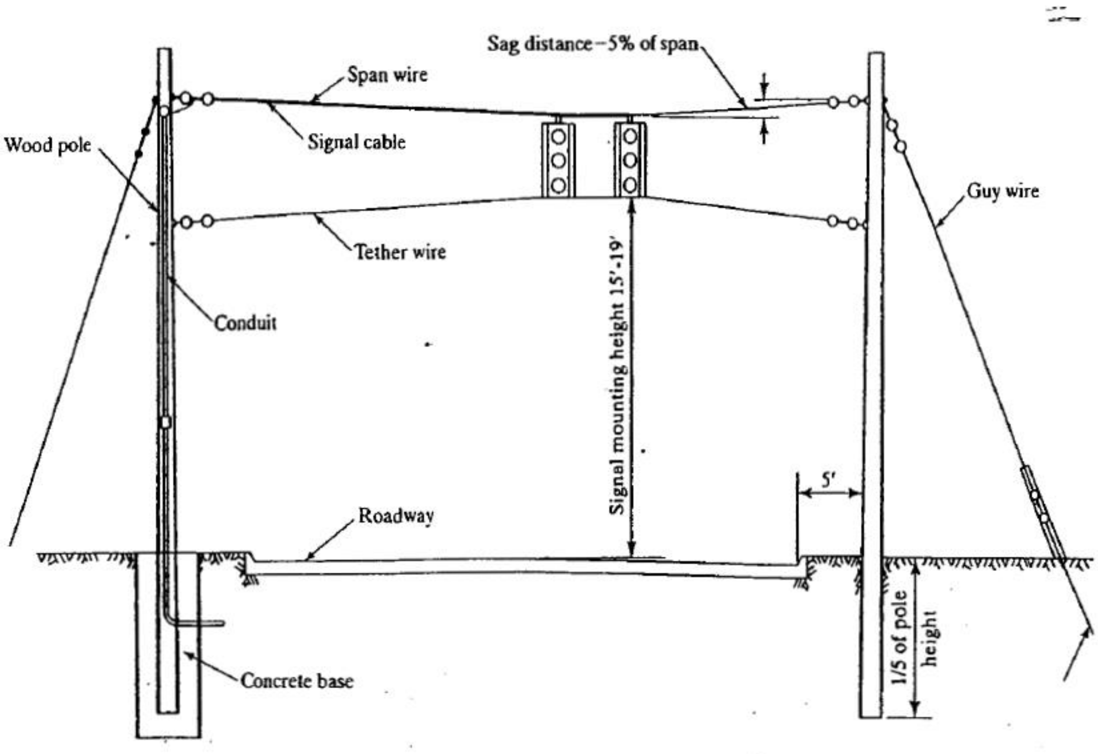


Figure 28: Use of Span Wire and Tether Wire Illustrated

(Source: Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., Manual of Traffic Signal Design, 2nd Edition, 1991.).

Figure 29 illustrates how power is supplied to a span-wire mounted signal head. A shielded power cable is wrapped around the primary support wire and connected to each signal head.

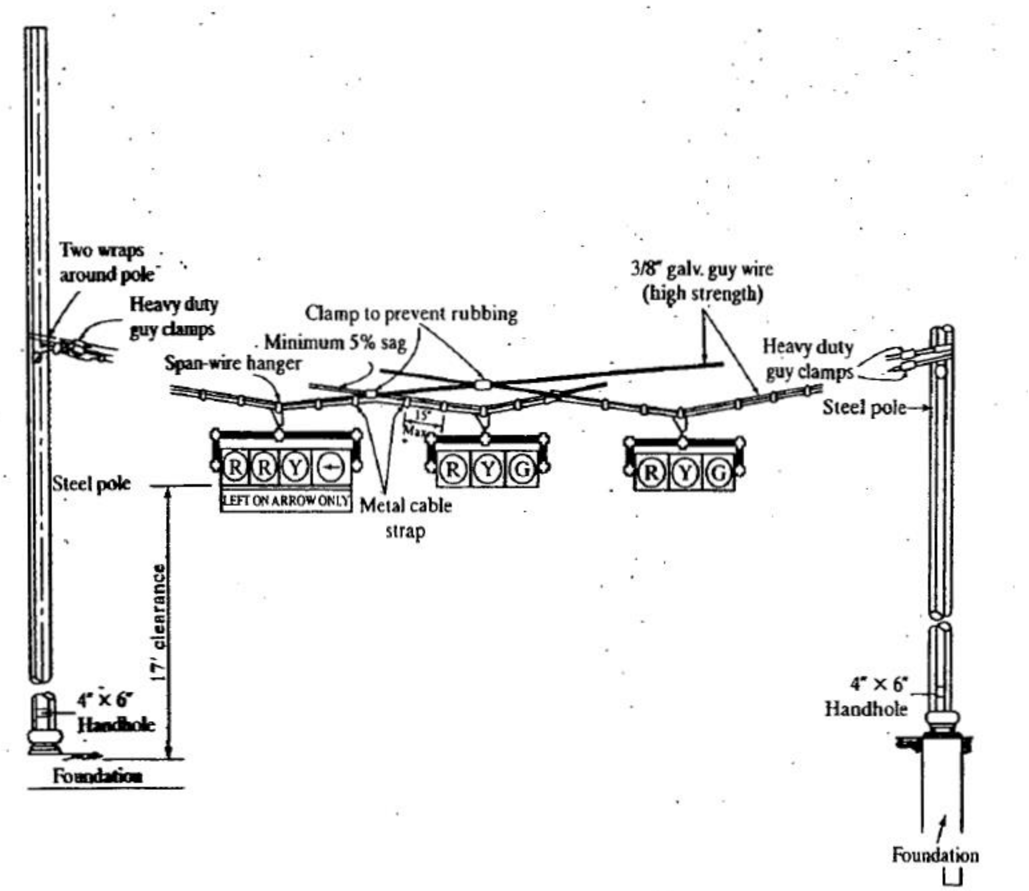


Figure 29: Providing Power to Span-Mounted Signals

(Source: Used with permission of Prentice-Hall Inc, Kell, J. and Fullerton, I., Manual of Traffic Signal Design, 2nd Edition, 1991.).

Figure 30 shows a typical field installation of span-wire mounted signals. In this case, a single span wire supports six signal heads that are sufficient to control all movements, including a left-turn phase on the major street.

Figure 30: A Typical Span-Wire Signal Installation.

Using the three signal mounting options (post mounted, mast-arm mounted, span-wire mounted), either alone or in combination, the traffic engineer can satisfy all of the posting requirements of the MUTCD and present drivers with clear and unambiguous operating instructions. Achieving this goal is critical to ensuring safe and efficient operations at signalized intersections.